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This paper summarizes the generic features and broad scope of F-15 and F-16 TGP tests, processes and basic theory as well as the development of rapid engineering tools. The tests and processes describe flight tests, data gathering, analyses and interpretation. The basic theory contains the derivation of coordinate transformations governing the dynamic motion of the laser beam. The rapid tools provide efficient capabilities to calculate targeting pod errors. The computational results compare TGP pointing-angle and laser-time-history data with the range Time Space Positioning Information (TSPI) data. As a result, flight test engineers can rapidly perform test and evaluation of the function and accuracy of current and future advanced laser TGP systems.

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FLIGHT TESTS, ANALYSES AND RAPID TOOLS FOR ADVANCED LASER TARGETING PODS

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ABSTRACT

This paper summarizes the generic features and broad scope of F-15 and F-16 TGP tests, processes and basic theory as well as the development of rapid engineering tools. The tests and processes describe flight tests, data gathering, analyses and interpretation. The basic theory contains the derivation of coordinate transformations governing the dynamic motion of the laser beam. The rapid tools provide efficient capabilities to calculate targeting pod errors. The computational results compare TGP pointing-angel and laser-time-history data with the range Time Space Positioning Information (TSPI) data. As a result, flight test engineers can rapidly perform test and evaluation of the function and accuracy of current and future advanced laser TGP systems.

The generic test processes and new automated software contain no aircraft or project specific features. The engineers may be able to reduce data, perform error analyses and obtain results within several days instead of a few weeks or even months. Employing the processes, methodologies and engineering tools described in the current paper, Global Power Fighters Combined Task Force (CTF) has successfully performed flight test and evaluation of TGP projects that were sponsored by both the United States Air Force and our European and Asian allies.

1.0 INTRODUCTION

Smart weapon system rely heavily on laser Targeting Pods (TGP) for accurate target designation and weapon delivery. The test, evaluation and analysis of such complex system present daily challenge to flight test engineers at Air Force Flight Test Center, AFFTC, Edwards AFB, California. The targeting pod air-to-ground mode includes sighting, tracking, and ranging features displayed on infrared and/or (CCD) video via the Multi-functional Display (MFD). The pod is designed as an aid for identifying, locating, and acquiring ground targets. The targeting pod provides the capability to deliver laser-guided bombs and conventional weapons. The targeting pod allows target acquisition and tracking with the following functions:

1. Laser designation for laser-guided bombs.
2. Line of sight and laser or passive ranging for ballistic weapon deliveries.
3. Target location for bombing geometry updates.

This paper presents the generic aircraft TGP laser time history data analysis methodology, a description of a VBA (Visual Basic Application) code and computational results. The purpose of the TGP laser time history data analyses is to verify proper function and accuracy by comparing the TGP laser time history data with the TSPI and the aircraft Fire Control Computer (FCC) or Modular Mission Computer (MMC) data. The code contains Macros that provide automatic functions of merging input data, executing the governing equations and plotting the results.

2.0 COORDINATE SYSTEMS AND TRANSFORMATIONS

Several coordinate systems are used as references during for the TGP time history analysis. This section presents each of these coordinate axis systems and the coordinate transformation law.

1. Aircraft Body Coordinate System
2. INS Platform Coordinate System

3. Along Track/ Cross Track/ Down Coordinate System
4. TSPI Coordinate Systems
5. Transformation Law
6. Coordinate Transformations

2.1 Aircraft Body Coordinate System:

Figure 1 illustrates the F-16 Body-Fixed Coordinate System. The positive X_B -, Y_B and Z_B - axes point through the nose of the aircraft, the right wing, and the bottom of the aircraft, respectively. The Center-of-Gravity (CG) is the origin of the body coordinate system.

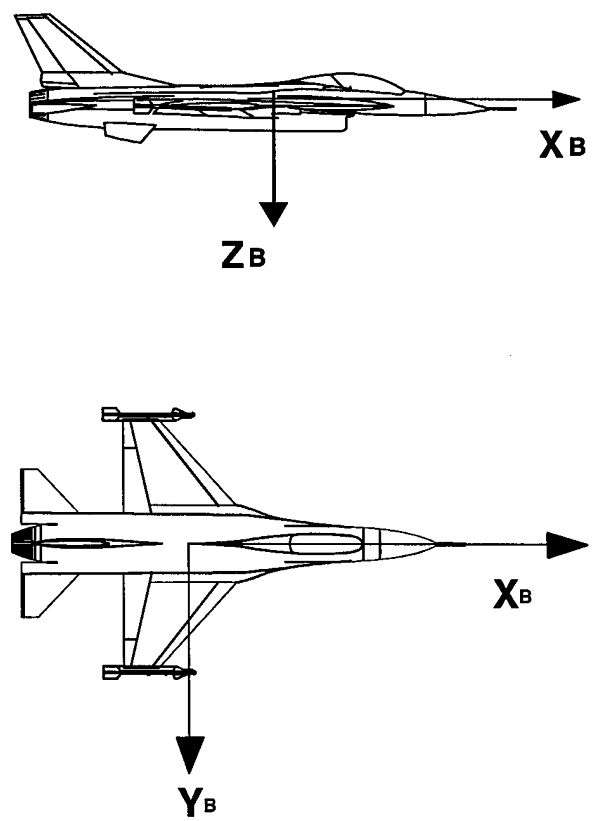


Figure 1. F-16 Body Coordinate System

2.2 INS Platform Coordinate System:

The INS Platform Coordinate System, illustrated in figure 2, has its X'', Y'' and Z'' axes fixed within the INS subsystem where the Platform positive Z''-axis is directed outward (or UP) off the page. All coordinate systems strictly follow the Right-Hand Rule. The relationships among Wander Angle, Platform Azimuth, Magnetic Variation, Magnetic Heading, True Heading, Ground Track Angle and AC Rotate Angle are also shown in figure 2.

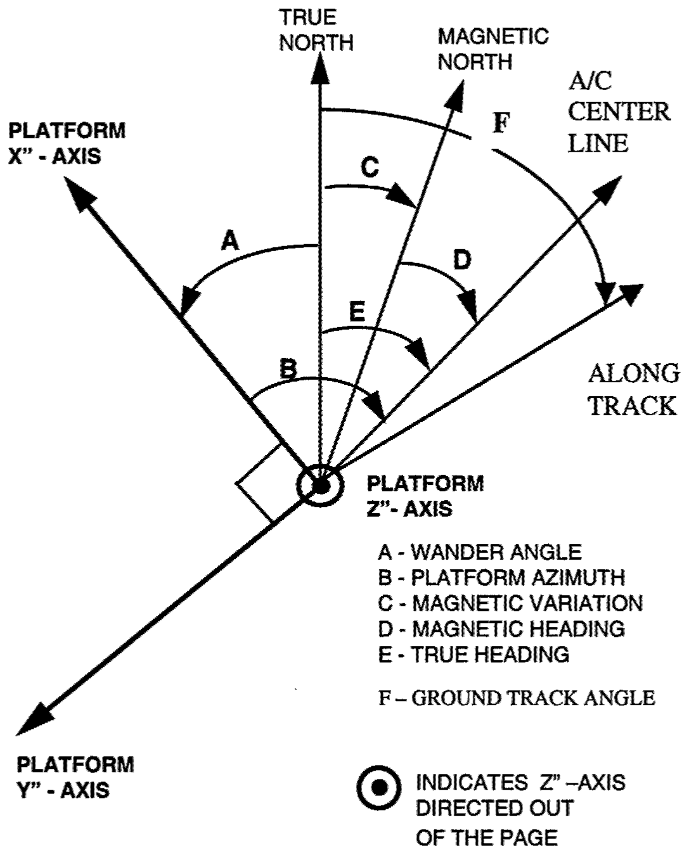


Figure 2. INS Platform Coordinate System

The Platform Azimuth (B), and True heading (E), are used to determine the Wander Angle (A). The Wander Angle is used to transform the platform X'', Y'' & Z'' to the East/North/Up Coordinate System. The angle of rotation of the aircraft, ACRotateAngle, introduced herein, is used to convert A/C Platform coordinate data to Along Track/Cross Track/Down coordinate data. The following equation shows that ACRotateAngle is a function of Wander Angle and the Ground Track Angle (GTA), F.

$$\begin{aligned} \text{ACRotateAngle} &= (\text{Platform Azimuth} - \text{True Heading Angle}) + \text{Ground Track Angle} \\ &= (B - E) + F = A + F \\ &= \text{Wander Angle} + \text{Ground Track Angle} \end{aligned}$$

2.3 Along Track/Cross Track/Down Coordinate System:

The Along Track, Cross Track and Down coordinate system is based on the aircraft heading with the X-axis pointing along the Ground Track of the aircraft. The Ground Track Angle is formed between True North and the Along Track axis. The Along Track, Cross Track and Down axes follow the Right-Hand Rule with the Down axis defined as positive pointing into the paper (see figures 2 and 6 for details).

2.4 TSPI Coordinate System:

The TSPI coordinate system is a ground-based system with its origin located at the target. At Edwards AFB, the X-, Y, and Z- axes point toward East, North and Up directions, respectively. The target range data are often measured between the target and the nose tip of the aircraft. As a result, the engineers usually request the TSPI data using the aircraft nose as the reference point (see figure 3 for details). When other reference points are employed, the users need to modify the code by following the methods documented in this paper. The TGP Line of Sight (LOS) looks down at the target. It also employs the aircraft platform based coordinates with origin located on the TGP.

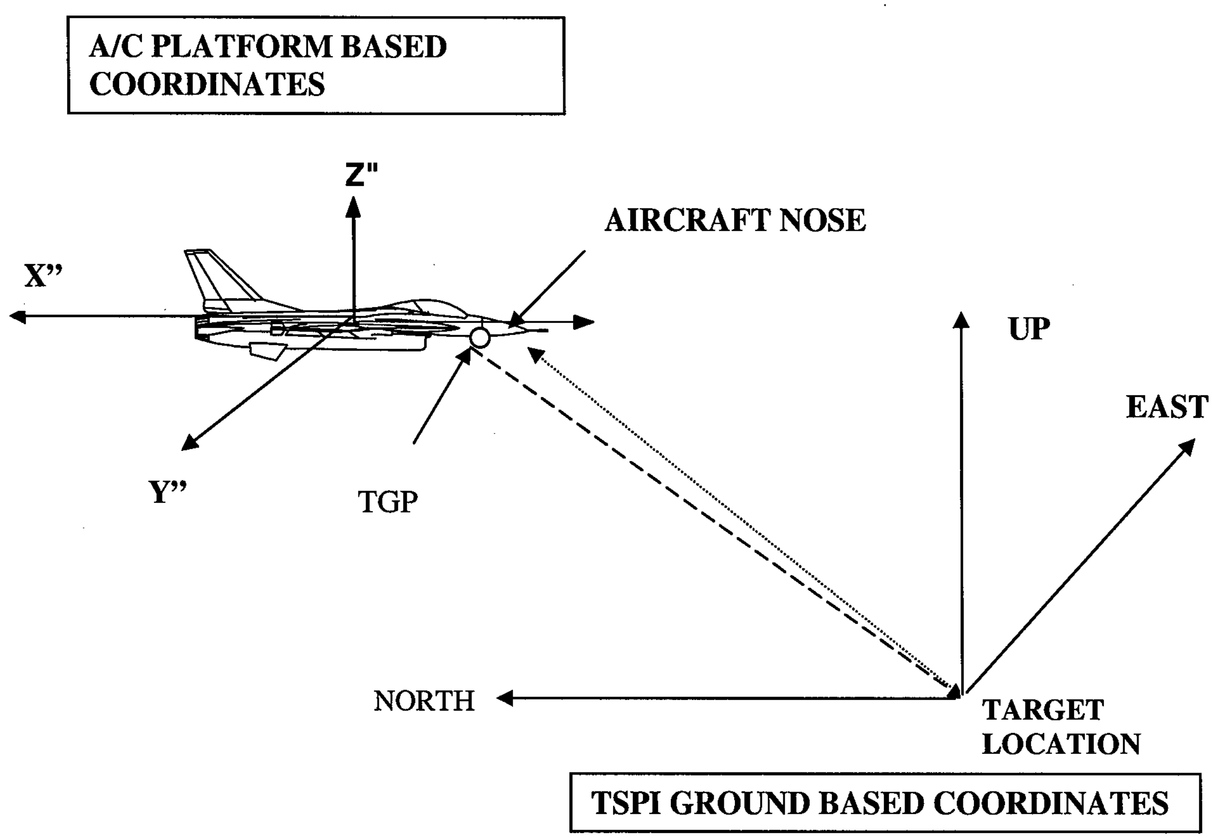


Figure 3. Platform and TSPI coordinates and Problem formulation

2.5 Transformation Law:

Cartesian tensors, vectors and transformation law will be discussed in this section. Two special types of tensors are frequently used in engineering applications. A Scalar or a quantity characterized by magnitude only is a tensor of zeroth order. A Vector, or a quantity characterized by both magnitude and direction, is a tensor of the first order. These and other higher order tensors are designated by the Index Notations. Using the Index Notations, any vector **A** located at an arbitrary point P in a rectangular coordinate can be written as:

$$\mathbf{A} = A_1\,\mathbf{e}_1 + A_2\,\mathbf{e}_2 + A_3\,\mathbf{e}_3$$

Where

$A_1 = Aa_1$
$A_2 = Aa_2$
$A_3 = Aa_3$
$A = (A_1\text{^}2 + A_2\text{^}2 + A_3\text{^}2)\text{^}0.5$
$a_1 = \text{COS}\ \Theta_1 = A_1 / A$
$a_2 = \text{COS}\ \Theta_2 = A_2 / A$
$a_3 = \text{COS}\ \Theta_3 = A_3 / A$

A_1, A_2 and A_3 are the rectangular projection of vector **A.**

a_1, a_2, and a_3 are the well-known direction Cosines of the line containing the vector **A** with respect to the (x_1, x_2, x_3) – axes.

In the Index Notation, Ai (i = 1, 2, 3) is the symbol used to designate the vector **A** in a three-dimensional space. It completely represents the vector **A.**

The vectors and direction Cosines are used frequently in this paper and are illustrated in figure 4. For illustration purposes, the Vector A may be envisioned as a laser beam emitting from the TGP towards the ground target. It thus has both direction and magnitude, with magnitude measured as the laser slant range. The projection of the laser beam on the x_1, x_2 and x_3 axes are the projected length A_1, A_2 and A_3. The angles formed between **A** and its projection $\mathbf{A_1}$, $\mathbf{A_2}$ and $\mathbf{A_3}$ are the direction cosines Θ_1, Θ_2 and Θ_3 respectively. In Section 4.0, we designate the values of the laser slant range, its associated projections and direction cosines as: LsrSlntRng; TGPX, TGPY, TGPZ; and DCOSX, DCOSY and DCOSZ, respectively.

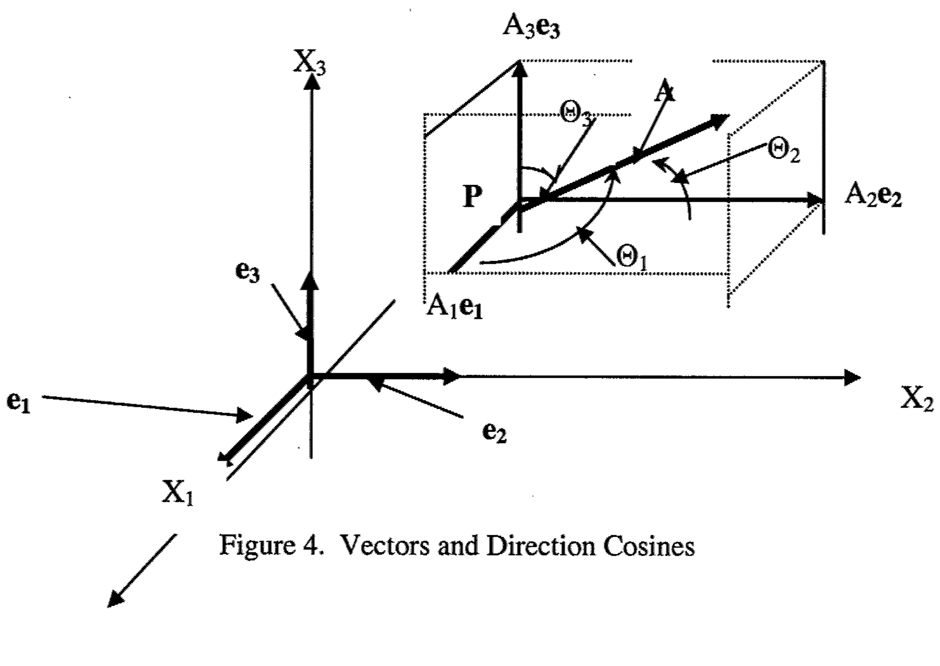


Figure 4. Vectors and Direction Cosines

2.6 Coordinate Transformations:

Figure 5 presents an example of basic 2-D coordinate transformation. In this figure there are two reference frames centered on the same point. An angle α is rotated from A to A' (or B to B'), positive in the clockwise direction and follows the Right-Hand Rule.

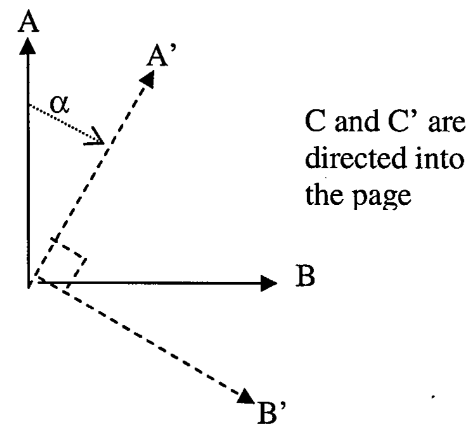


Figure 5. Two-Dimensional Coordinate Transformation

Transforming the A-B coordinates the to A'-B' reference frame requires a rotation in the same direction as the angle is measured. This is performed by direct visualization:

$$\begin{aligned} A' &= A * \mathrm{COS}(\alpha) + B * \mathrm{SIN}(\alpha) \\ B' &= -A * \mathrm{SIN}(\alpha) + B * \mathrm{COS}(\alpha) \\ C' &= C \end{aligned}$$

In matrix format, we have:

$$\begin{bmatrix} A' \\ B' \\ C' \end{bmatrix} = \begin{bmatrix} \mathrm{COS}(\alpha) & \mathrm{SIN}(\alpha) & 0 \\ -\mathrm{SIN}(\alpha) & \mathrm{COS}(\alpha) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} A \\ B \\ C \end{bmatrix}$$

Transforming the A'-B' coordinates to the A-B reference frame requires a rotation in the opposite (or negative) direction as the angle is measured. This is done by the following equation:

$$\begin{bmatrix} A \\ B \\ C \end{bmatrix} = \begin{bmatrix} \mathrm{COS}(-\alpha) & \mathrm{SIN}(-\alpha) & 0 \\ -\mathrm{SIN}(-\alpha) & \mathrm{COS}(-\alpha) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} A' \\ B' \\ C' \end{bmatrix}$$

Several pertinent coordinate transformations are presented below for reader's reference. It is noted herein that the purpose of coordinate transformation in this paper is to provide a common reference system so data obtained from different sources using different coordinates may be compared using the same common coordinate system.

2.6.1 INS Platform To East/North/Up

Data required are: Platform Azimuth (PltfAZ)
True Heading (ACHdg)
A/C X INS component (X")
A/C Y INS component (Y")
A/C Z INS component (Z")

Where Wander Angle = PltfAZ – ACHdg = A

Note the Up-axis and the Z"- axis are pointing in opposite directions. The Up-axis is positive pointing into the paper whereas the Z"- axis is positive pointing out of the paper. Applying direct visualization of the coordinate systems as illustrated in figure 5, yields the following transformation equations:

$$
\begin{aligned}
\text{East} &= -X'' * \text{SIN}(A) - Y'' * \text{COS}(A) \\
\text{North} &= X'' * \text{COS}(A) - Y'' * \text{SIN}(A) \\
\text{Up} &= -Z''
\end{aligned}
$$

Or in matrix format,

$$
\begin{bmatrix} E \\ N \\ U \end{bmatrix} = \begin{bmatrix} -\text{SIN}(A) & -\text{COS}(A) & 0 \\ \text{COS}(A) & -\text{SIN}(A) & 0 \\ 0 & 0 & -1 \end{bmatrix} \begin{bmatrix} X'' \\ Y'' \\ Z'' \end{bmatrix}
$$

2.6.2 East/North/Up To Along Track/Cross Track/Down

GTA = Ground Track Angle
Measure (+) from North to Along Track

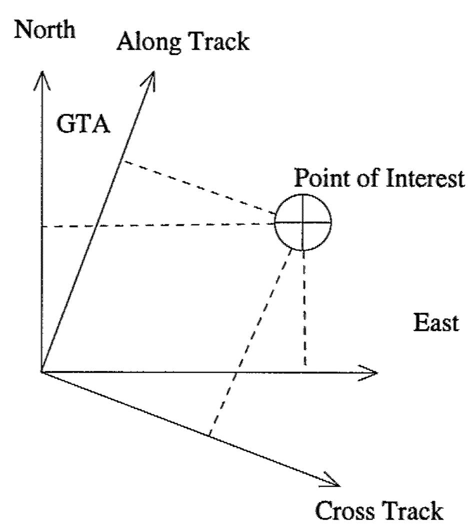


Figure 6. Rotation from East/North/Up to Along Track/Cross Track and Down

The transformation from East/North/Up to Along Track/Cross Track/Down is extensively used in this paper. By following the Right-Hand Rule, the Up-axis is defined as positive and points out of the paper whereas the Down-axis is negative and points into the paper. The value of the GTA may be obtained from either TPSI or A/C data. If comparisons are between the TGP and TSPI, then GTA based on TSPI should be requested.

Data required are: Ground Track Angle (GTA)
East component data (E)
North component data (N)
Up component data (U)

Using the coordinate transformation in the direction of GTA, results in the following equations:

Along Track (AT) = N * COS(GTA) + E * SIN(GTA)
Cross Track (CT) = - N * SIN(GTA) + E * COS(GTA)
Down (D) = - U

The corresponding Matrix for the above equations is:

$$\begin{bmatrix} AT \\ CT \\ D \end{bmatrix} = \begin{bmatrix} \mathrm{COS\ (GTA)} & \mathrm{SIN\ (GTA)} & 0 \\ \mathrm{-SIN\ (GTA)} & \mathrm{COS\ (GTA)} & 0 \\ 0 & 0 & -1 \end{bmatrix} \begin{bmatrix} N \\ E \\ U \end{bmatrix}$$

The reverse transformation from Along Track/Cross Track/Down to East/North/Up coordinates is shown below:

Data required are: Ground Track Angle
Along Track component data
Cross Track component data
Down component data

Using the coordinate transformation in the opposite direction of the measured GTA yields the following equations and their Matrix representations:

N = North = AT * COS(-GTA) + CT* SIN(-GTA)
E = East = - AT* SIN(-GTA) + CT* COS(-GTA)
U = Up = - D

$$\begin{bmatrix} N \\ E \\ U \end{bmatrix} = \begin{bmatrix} \mathrm{COS\ (-GTA)} & \mathrm{SIN\ (-GTA)} & 0 \\ \mathrm{-SIN\ (-GTA)} & \mathrm{COS\ (-GTA)} & 0 \\ 0 & 0 & -1 \end{bmatrix} \begin{bmatrix} AT \\ CT \\ D \end{bmatrix}$$

2.6.3 INS Platform To Along Track/ Cross Track/Down

The transformation from INS Platform coordinates to Along Track/Cross Track/Down is also extensively used in this paper. By following the Right-Hand Rule, the Down axis and the Platform Z"- axis are pointing in opposite directions.

Data required: Platform Azimuth (PltfAZ)
True Heading (ACHdg)
A/C X INS component data (X")
A/C Y INS component data (Y")
A/C Z INS component data (Z")
Ground Track Angle (GTA)

Where Rotation Angle (ϕ) = Platform Azimuth – True Heading Angle + Ground Track Angle

Using the coordinate transformation in the direction of GTA, one obtains

Along Track = X" * COS(ϕ) - Y" * SIN(ϕ)
Cross Track = - X" * SIN(ϕ) - Y" * COS(ϕ)]
Down = -Z"

The corresponding matrix representation is shown below:

$$\begin{bmatrix} AT \\ CT \\ D \end{bmatrix} = \begin{bmatrix} \text{COS}(\phi) & -\text{SIN}(\phi) & 0 \\ -\text{SIN}(\phi) & -\text{COS}(\phi) & 0 \\ 0 & 0 & -1 \end{bmatrix} \begin{bmatrix} X'' \\ Y'' \\ Z'' \end{bmatrix}$$

3.0 AIRCRAFT AND TSPI TIME HISTORY DATA

For illustration purposes (see Figure 3), we consider the F-16 test aircraft flying towards South with its platform coordinates X"- ,Y"- and Z"- axes fully aligned using the Ring Laser Gyro (RLG). The X"-axis points out from the tail of the aircraft whereas Y"- and Z"- axes align in the directions following the Right-Hand rule. The TGP is located on the right side of the aircraft and the pilot designates the laser beam on the target. The TSPI uses a ground based coordinate system with its origin located at the target. Without loss of generality, we selected the aircraft nose as the TSPI data reference point. Other points such as the aircraft CG and the INS location may also be used as reference points. In order to directly apply the VBA code described in this paper, the user must request the TSPI data referencing the aircraft nose.

The TSPI target data are therefore measured between the aircraft nose and the TSPI coordinate origin with coordinates point in the East-, North- and Up- directions, depicted in figure 3. Before using the time history data, both the Aircraft based Platform data and the ground based TSPI data must be transformed to the Along Track/Cross Track/Down data. As a result, all comparisons can be referenced to the same Along Track/Cross Track/Down coordinate system. The methods of coordinate transformation presented in Section 2 are utilized. Section 3.1 and 3.2

present the detailed methods of transformation for the A/C Platform data and the TSPI data, respectively.

3.1 Aircraft Data Transformation:

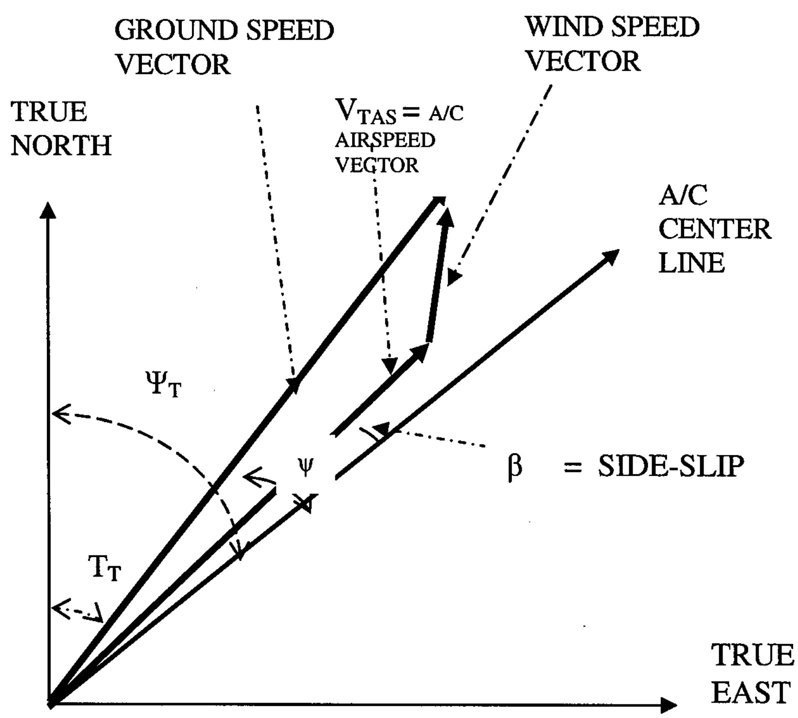
The parameters used in this paper follow the syntax used in Visual Basic. For example, Aircraft Rotate Angle and TSPI Rotate Angle are represented by ACRotateAngle and TSPIRotateAngle, respectively.

This section presents the governing equations to convert the input data from the A/C Platform Coordinate System to the Along Track/Cross Track/Down Coordinate System. Referring to Section 2.2 and 2.6.3, the Aircraft Angle of Rotation, ACRotateAngle, is applied herein to convert input data.

ACRotateAngle = Platform Azimuth – True Heading Angle + Ground Track Angle

The Drift Angle, Ψ, provides the angular relationship between the GTA and the True Heading Angle of the aircraft. Figure 7 shows that the GTA is created due to the influence of the wind velocity vector. Without the drift angle, the GTA reverts back to the True Heading Angle. The side-slip angle, β, is defined as the angle between the airspeed vector and the A/C center line. If the wind speed vector becomes zero, the A/C drift angle is equal to the side-slip angle.

Drift Angle = True Heading Angle – Ground Track Angle



T_T = GTA = GROUND TRACK ANGLE
Ψ_T = A/C TRUE HEADING
β = A/C SIDE-SLIP ANGLE
Ψ = **A/C DRIFT ANGLE** = A/C TRUE HEADING – GTA = $\Psi_T - T_T$

Figure 7. Difference between Aircraft Drift Angle and Side Slip Angle

Data required: Platform Azimuth (PltfAZ)
True Heading (ACHdg)
A/C INS Platform based Range-to-Target X"-component data(ACX)
A/C INS Platform based Range-to-Target Y"-component data(ACY)
A/C INS Platform based Range-to-Target Z"-component component data(ACZ)
Ground Track Angle (GTA)

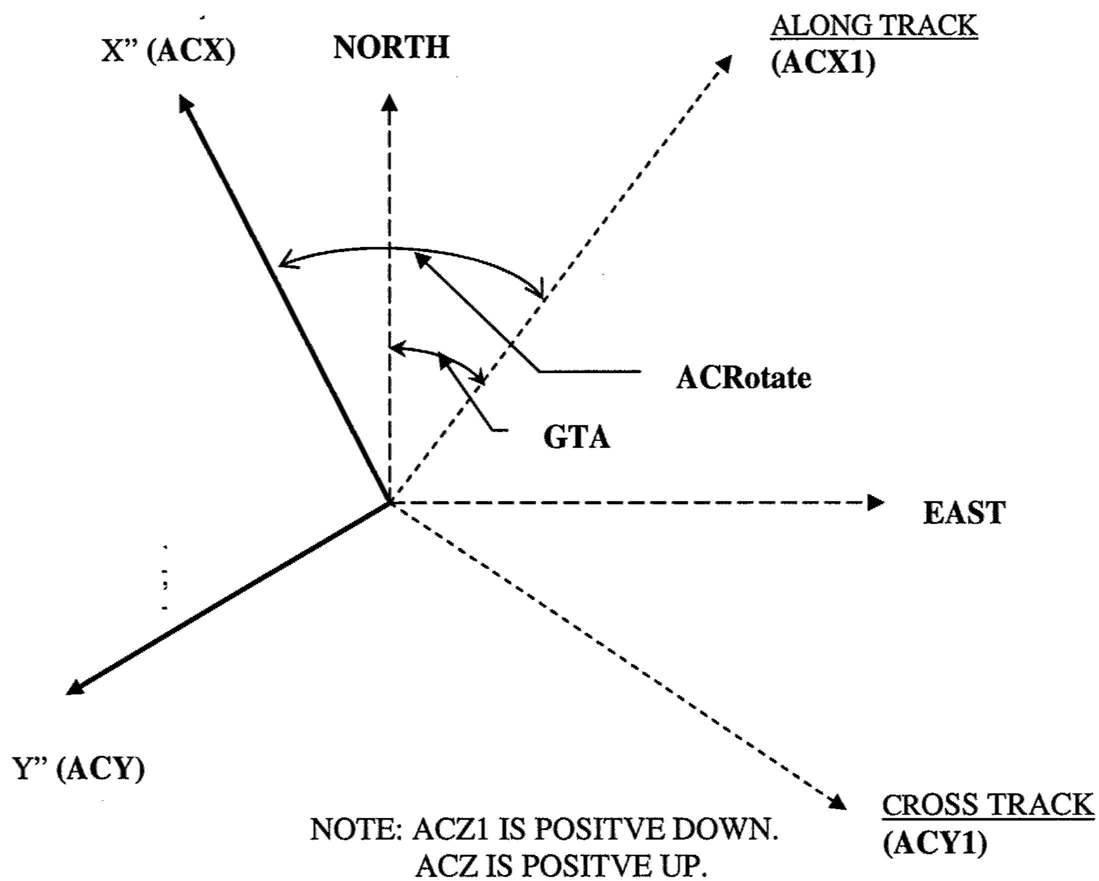


Figure 8. Transformation of Aircraft Platform Coordinates to Along/Cross Coordinates

Referring to figure 8 and using the ACRotate Angle and the FCC Range-to-Target data ACX, ACY and ACZ, the A/C Platform Coordinate based FCC data can be converted to the Along Track/Cross Track/Down Coordinate based data ACX1, ACY1 and ACZ1. The governing equations are:

$$ACX1 = ACX * COS(ACRotateAngle) - ACY * SIN(ACRotateAngle)$$
$$ACY1 = -ACX * SIN(ACRotateAngle) - ACY * COS(ACRotateAngle)$$
$$ACZ1 = -ACZ$$

In Matrix expression, the previous equations are shown as:

$$\begin{bmatrix} ACX1 \\ ACY1 \\ ACZ1 \end{bmatrix} = \begin{bmatrix} COS\ (ACRotateAngle) & -\ SIN\ (ACRotateAngle\ ) & 0 \\ -\ SIN\ (ACRotateAngle) & -\ COS\ (ACRotateAngle\ ) & 0 \\ 0 & 0 & -1 \end{bmatrix} \begin{bmatrix} ACX \\ ACY \\ ACZ \end{bmatrix}$$

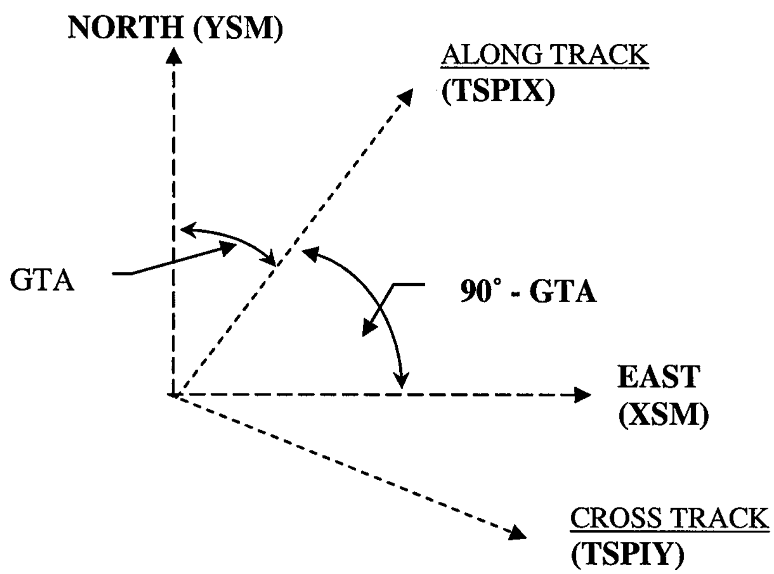
Using equations shown in Section 2.5, the aircraft based Slant Range can be calculated by:

ACSR = SQRT(ACX1^2 + ACY1^2 + ACZ1^2)

3.2 TSPI Data Transformation:

This section shows the conversion of the TSPI based target data (XSM, YSM, ZSM) in East/North/Up coordinate system to the target data (TSPIX, TSPIY, TSPIZ) in the Along Track/Cross Track/Down Coordinate System, figure 9. Therefore, XSM, YSM and ZSM are TSPI data prior to the conversion and TSPIX, TSPIY and TSPIZ are the TSPI data after the conversion. TSPIRotate (TSPIRotate = 90° - GTA) is the angle used for the data conversion.

Often, TSPI based HVN is used in the above equation instead of TSPI based GTA. The HVN is not the true GTA, but an approximation of the GTA in a local area. When ordering the TSPI data, true TSPI based GTA should be requested instead of HVN.



NOTE: XSM, YSM and ZSM are TSPI data.
ZSM IS POSITIVE UP. TSPIZ IS POSITVE DOWN
ZSM IS IN THE EAST/NORTH/UP COORDINATES.
TSPIZ IS IN THE ALONG TRACK/CROSS TRACK/DOWN COORDINATES

Figure 9. Transformation of TSPI Coordinates to Along Track/Cross Track/Down Coordinates

Data required: TSPI based Range-to-Target East component data(XSM)
TSPI based Range-to-Target North component data(YSM)
TSPI based Range-to-Target Up component data(ZSM)
Ground Track Angle (GTA)

3.2.1 Coordinate Rotation

To convert the TSPI Range-to-Target data in East/North/Up coordinate system to Along Track/Cross Track/Down coordinate system, we use the following coordinate transformation:

$$TSPIX = XSM * COS(TSPIRotateAngle) + YSM * SIN(TSPIRotateAngle)$$
$$TSPIY = XSM * SIN(TSPIRotateAngle) - YSM * COS(TSPIRotateAngle)$$
$$TSPIZ = - ZSM$$

or in Matrix format:

$$\begin{bmatrix} TSPIX \\ TSPIY \\ TSPIZ \end{bmatrix} = \begin{bmatrix} COS\ (TSPIRotateAngle) & SIN\ (TSPIRotateAngle) & 0 \\ SIN\ (TSPIRotateAngle) & -COS\ (TSPIRotateAngle) & 0 \\ 0 & 0 & -1 \end{bmatrix} \begin{bmatrix} XSM \\ YSM \\ ZSM \end{bmatrix}$$

3.2.2 Coordinate Translation

To convert the data from the aircraft nose to other reference locations, in addition to coordinate rotation, coordinate translation must be performed. The TGP is located on the right side of the aircraft, 14 feet aft of and 3 feet lower than the nose of the aircraft. Should TGP be located elsewhere in the future, said numbers may be replaced with other numbers that reflect the actual location of the TGP. All TSPI data should be ordered referencing to the aircraft nose. The first set of translation equations are used to transfer the TSPI data from the aircraft nose to the TGP location.

$$TSPIXtgp = TSPIX - 14 * COS(PitchAngle) * COS(DriftAngle) + 3 * SIN(PitchAngle) * COS(DriftAngle) - 3*COS(PitchAngle)*SIN(DriftAngle)$$

$$TSPIYtgp = TSPIY - 14 * COS(PitchAngle) * SIN(DriftAngle) + 3 * COS(DriftAngle)$$

$$TSPIZtgp = TSPIZ + 14 * SIN(PitchAngle) + 3 * COS(PitchAngle)$$

The CG of the aircraft is 30 feet from the nose. Similarly, the governing equations for translating TSPI data from the aircraft nose to the aircraft CG location are shown below. Again, should CG location be changed, said number may be replaced with other numbers that reflect the actual CG location of the aircraft.

TSPIXcg = TSPIX - 30 * COS(PitchAngle) * COS(DriftAngle)
TSPIYcg = TSPIY - 30 * COS(PitchAngle) * SIN(DriftAngle)
TSPIZcg = TSPIZ + 30 * SIN(PitchAngle)

The TSPI Slant Range equations based on aircraft CG and TGP data are:

TSPISRcg = SQRT(TSPIXcg^2 + TSPIYcg^2 + TSPIZcg^2)
TSPISRtgp = SQRT(TSPIXtgp^2 + TSPIYtgp^2 + TSPIZtgp^2)

The above equations can be verified by using small angles of approximation.

Referring to figure 10, the origin of the TGP coordinates is located on the right bottom side of the aircraft nose whereas the origin of the TSPI coordinates rests on the target. The target is ahead of the aircraft and on the same side of the TGP. The laser beam represented by TGP vector **A** is pointing 'down' and 'forward' at the laser designation point' i.e., the target. However, there are errors such that the TGP measurement may be inaccurate. These errors pertain to slant range and its projections, elevation, azimuth, etc. The target component distances (distance between the TGP and the target) are ACX1, ACY1 and ACZ1 and are positive values. On the other hand, the TSPI coordinate origin is located on the target and the TSPI vector **B** is pointing 'up' and 'backward' at the TGP (see Figure 10). The target component distances are TSPIX, TSPIY and TSPIZ and are negative values. This is because the TSPI axes are pointing forward, right and downward, whereas the TGP is behind, on the left side and above the target.

Total distance of each component = component distance measured between the nose tip to the target + component distance between the nose tip to the TGP.

Noting that the values TSPIX, TSPIY and TSPIZ are negative, the total distance measured between the target and the TGP in three components becomes:

TSPIXtgp = TSPIX – [14 * COS(PitchAngle) - 3 * SIN(PitchAngle)]
TSPIYtgp = TSPIY + 3
TSPIZtgp = TSPIZ + [14 * SIN(PitchAngle) + 3 * COS(PitchAngle)]

Similarly, the following equations can be obtained by limiting the aircraft excursion in the horizontal plane.

TSPIXtgp = TSPIX – [14 *COS(DriftAngle) + 3 * SIN(DriftAngle)]
TSPIYtgp = TSPIY – 14 [SIN(DriftAngle) + 3 * COS(DriftAngle)]
TSPIZtgp = TSPIZ + 3

When Pitch Angle = $\Theta = 0°$, the first set of translation equations convert directly to the above equations.

By limiting the conditions to $\Theta = \psi = 0°$, both the first set of translation equations and figure 13 show:

TSPIXtgp = TSPIX – 14
TSPIYtgp = TSPIY + 3
TSPIZtgp = TSPIZ + 3

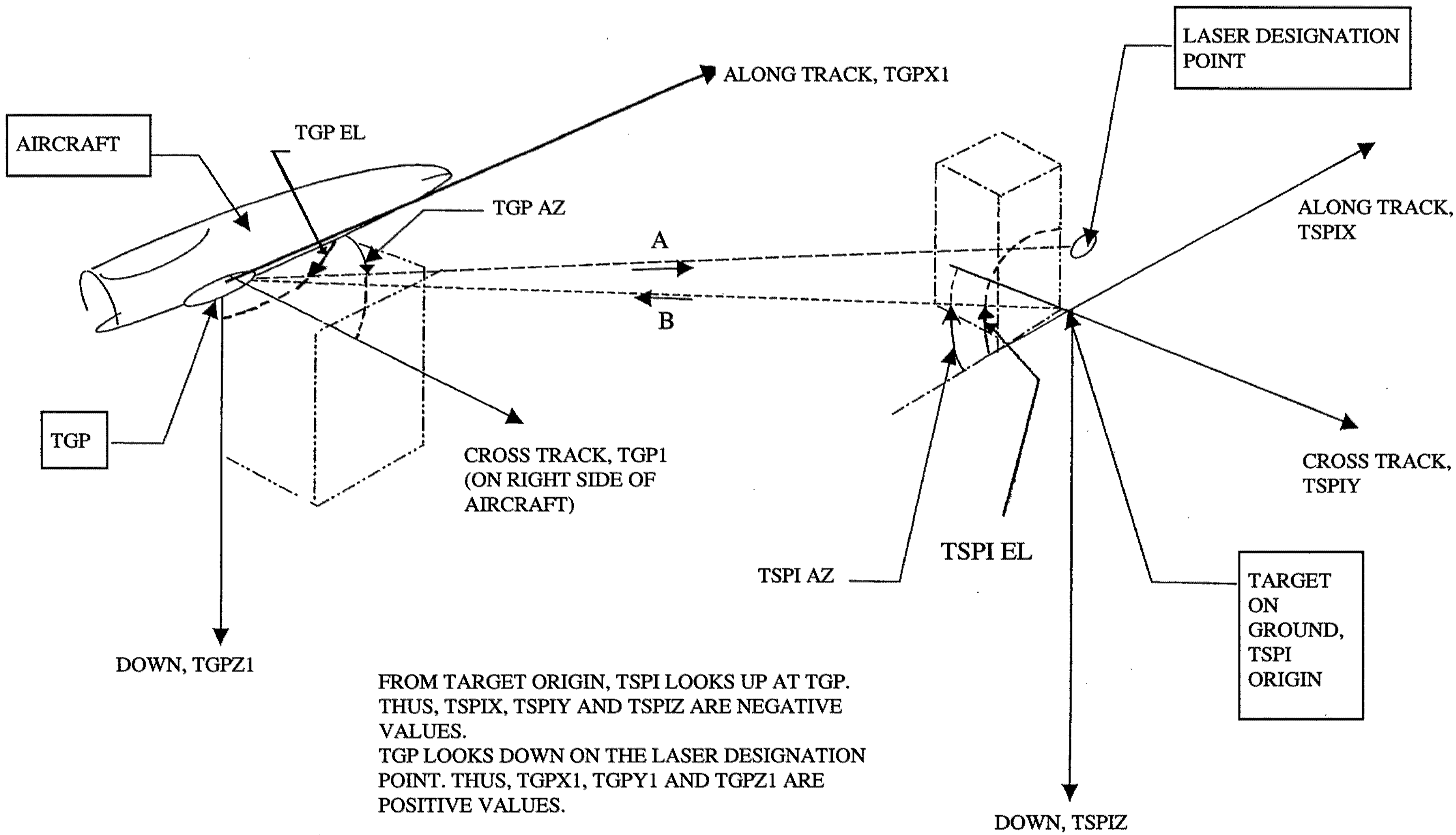


Figure 10 TGP Error Analysis and Along Track System

4.0 TGP LASER TIME HISTORY DATA

Data required: TGP Laser measured Slant Range (LsrSlntRng)
Aircraft Body Fixed Range–to-Target X-component data, X_B
Aircraft Body Fixed Range–to-Target Y-component data, Y_B
Aircraft Body Fixed Range–to-Target Z-component data, Z_B
TGP measured X-component Direction Cosine, DCOSX
TGP measured Y-component Direction Cosine, DCOSY
TGP measured Z-component Direction Cosine, DCOSY
Platform Azimuth (PltfAZ)
True Heading (ACHdg)
Ground Track Angle (GTA)

Both the Laser Slant Range and the Direction Cosines are known TGP measured values. The Laser Range components, TGPX, TGPY and TGPZ in the Platform Coordinates can be calculated by using both the Laser Slant Range and its associated Direction Cosines:

TGPX = LsrSlntRng * DCOSX
TGPY = LsrSlntRng * DCOSY
TGPZ = LsrSlntRng * DCOSZ

The Fire Control Computer (FCC) or Modular Mission Computer (MMC) calculated FCC/MMC Slant Range (FCCSlntRng), may base on the aircraft body coordinates. This is different from the LsrSlntRng measured by the TGP. The governing equation for the FCC/MMC Slant Range (FCC/MMC Range to Target) may be expressed by:

$$\text{FCCSlntRng} = \text{SQRT}(X_B\text{^}2 + Y_B\text{^}2 + Z_B\text{^}2)$$

The A/C Platform based data must be converted to the Along Track/Cross Track/Down data for data comparisons. The angular relationship between the Platform Coordinates and the Along Track/Cross Track/Down Coordinates is again:

ACRotateAngle = PltfAZ – True Heading + GTA

Using methods described in Section 6, the Rotation from Platform to Along Track/Cross Track/Down Coordinates becomes:

TGPX1 = TGPX * COS(ACRotateAngle) - TGPY * SIN(ACRotateAngle)
TGPY1 = - TGPX * SIN(ACRotateAngle) - TGPY * COS(ACRotateAngle)
TGPZ1 = - TGPZ

The corresponding Matrix format is:

$$\begin{bmatrix} \text{TGPX1} \\ \text{TGPY1} \\ \text{TGPZ1} \end{bmatrix} = \begin{bmatrix} \text{COS (ACRotateAngle)} & \text{- SIN (ACRotateAngle)} & 0 \\ \text{- SIN (ACRotateAngle)} & \text{- COS (ACRotateAngle)} & 0 \\ 0 & 0 & -1 \end{bmatrix} \begin{bmatrix} \text{TGPX} \\ \text{TGPY} \\ \text{TGPZ} \end{bmatrix}$$

5.0 COMPARISONS OF TIME HISTORY DATA

The laser timing and A/C Platform based data can be compared against the TSPI data to verify their accuracies and functionality. Referring to figure 10, the following equations can be used to determine the elevation angles, azimuth angles, elevation errors, azimuth errors, Along Track/Cross Track/Down errors, laser range errors at the TGP location and laser range errors at the aircraft CG.

The governing equations for the Target Pod Elevation and Azimuth Angles (degrees) are:

TGPEL1 = ATAN (TGPZ1 / (SQRT(TGPX1^2 + TGPY1^2)))
TGPAZ 1= ATAN (TGPY1 / TGPX1)

(It is noted herein that TGPEL1 is the **correct** expression for the TGP elevation, not TGPEL below).

In order to satisfy the definition of TGP Elevation Angle Error so that the TGP is long when Elevation Angle error is positive, we **artificially** changed the sign of TGPZ1 to negative. This yields:

TGPEL = ATAN (-TGPZ1 / (SQRT(TGPX1^2 + TGPY1^2)))
TGPAZ = ATAN (TGPY1 / TGPX1)

The governing equations for the TSPI Elevation and Azimuth Angles (degrees) are:

TSPIEL = ATAN (TSPIZtgp / (SQRT(TSPIXtgp^2 + TSPIYtgp^2)))
TSPIAZ = ATAN (TSPIYtgp / TSPIXtgp)

The Elevation Angle Errors for TGP (mils) becomes:

ELError_tgp = (TGPEL - TSPIEL) * (π / 180) * 1000

Note: (+) indicates the TGP is long of the target
(-) indicates the TGP is short of the target
Although labeled as mils, the actual value is in millirads which are approximately mils at small angles

The Azimuth Angle Errors for TGP (mils) is:

AZError_tgp = (TGPAZ - TSPIAZ) * (π / 180) * 1000

Note: (+) indicates the TGP is right of the target
(-) indicates the TGP is left of the target

The Range-to-Target error in the direction of Along Track, Cross Track and Down axes for the TGP (feet) are:

AlongError_TGP = TGPX1 + TSPIXtgp
CrossError_TGP = TGPY1 + TSPIYtgp
DownError_TGP = TGPZ1 + TSPIZtgp

Note: (+) indicates the TGP is long, right, and below the target
(-) indicates the TGP is short, left, and above the target.

The Laser Slant Range Error for the TGP (feet) is:

LsrRngError = LsrSlntRng – TSPISlntRng

LsrSlntRng is the TGP laser slant range measured at the TGP location. TSPISlntRng is the TSPI slant range measured at the TGP location and is governed by the following equation:

TSPISlntRng = SQRT (TSPIXtgp ^2 + TSPIYtgp ^2 + TSPIZtgp ^2)

The FCC A/C platform based Elevation and Azimuth Angles for the TGP in the Along Track/Cross Track/Down axes are (degrees):

ACEL = ATAN (-ACZ1 / (SQRT(ACX1^2 + ACY1^2)))
ACAZ = ATAN(ACY1 / ACX1)

The FCC A/C platform based Range-to-Target Errors referrenced to the aircraft CG location for the TGP in the Along Track/Cross Track/Down axes are:

AlongError_TGPcg = ACX1 + TSPIXcg
CrossError_TGPcg = ACY1 + TSPIYcg
DownError_TGPcg = ACZ1 + TSPIZcg

The FCC aircraft platform based slant range error for the TGP referred to the aircraft CG location is:

CGSlntRngError = ACSlntRng – TSPISlnRng(cg)

Where ACSlntRng = ACSR = SQRT (ACX1 ^2 + ACY1 ^2 + ACZ1 ^2)
TSPISlntRng = SQRT (TSPIXcg ^2 + TSPIYcg ^2 +TSPIZcg ^2)

6.0 INPUTS AND OUTPUTS

Input Data Required:

The input data required for TGP time histories calculations are taken from the following sources:

- TSPI
- AMUX (Target Pod Data)
- DMUX (INU Data)

- Data Pump
  - AMUX for Block 30
  - BMUX for Block 40
  - CMUX for Block 50 and MMC

The following tables list the parameters needed from the data sources.

Table 1. List of TSPI parameters

Parameter Name	Parameter Description
XSM	Range to Target (East), TSPI Data
YSM	Range to Target (North), TSPI Data
ZSM	Range to Target (Elevation), TSPI Data
SR	Slant Range
GTA	Ground Track Angle

Table 2. List of AMUX TGP parameters

Parameter Name	Parameter Description
DCOSX	Laser LOS direction Cosine X
DCOSY	Laser LOS direction Cosine Y
DCOSZ	Laser LOS direction Cosine Z
LsrRng	Laser Slant Range

Table 3. List of DMUX parameters

Parameter Name	Parameter Description
Pitch	Aircraft PitchAngle
ACHDG	Aircraft True Heading Angle
PltfmAZ	Platform Azimuth Angle

Table 4. Data Pump Parameters

Parameter Name	Parameter Description
ACX	Range to Target X, Aircraft Platform Data
ACY	Range to Target Y, Aircraft Platform Data
ACZ	Range to Target Z, Aircraft Platform Data
ACGTA	Aircraft Ground Track Angle, GTA

<u>Output Data:</u>

The pertinent output data are plotted in graphic formats. They can include laser range, laser range error, azimuth angle, azimuth angle error, elevation angle, elevation angle error and along track/cross track/down error. From a targeting pod standpoint, we are primarily interested in laser range error, targeting pod azimuth angle error, and targeting pod elevation angle error.

7.0 APPLICATION FOR TARGETING POD ANALYSIS

7.1 Test and Analysis

Once a targeting pod mission is successfully flown, the video and mux data are dupped. The video data is classified a minimum of confidential until a video review is accomplished. The mux data is classified confidential because the DTC (data transfer cartridge) was loaded from a classified computer. Once the tapes are received the required mux (AMUX, BMUX, and DMUX) and TSPI (Time Space Position Information) data are ordered in rdf (raw data file) format. While waiting for the rdf files, the video tapes are reviewed to determine the time slices for which analysis is to be performed.

The classified mux data tape is then process on a classified computer to strip out the unclassified data blocks that contain the data that is needed for analysis. The resultant data is then declassified for analysis on a desktop PC where an Excel spreadsheet or current VBA code (input - Figure 11 and output – Figure 12) is then used to strip out the desired parameters, merge the various data parameters with the TSPI data (Figure 13), and perform the analysis. Ahead time is now always 0 as the MUX data and the TSPI data are now synced to GPS time.

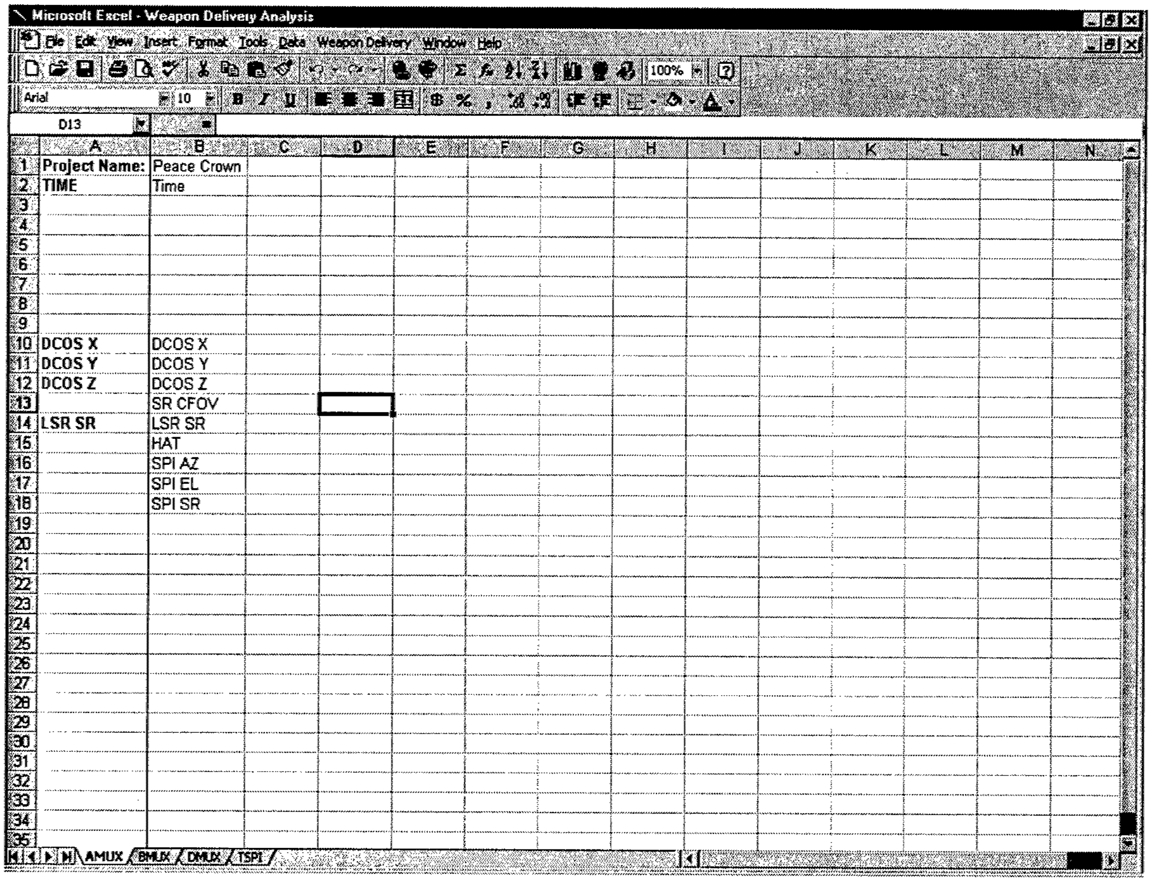
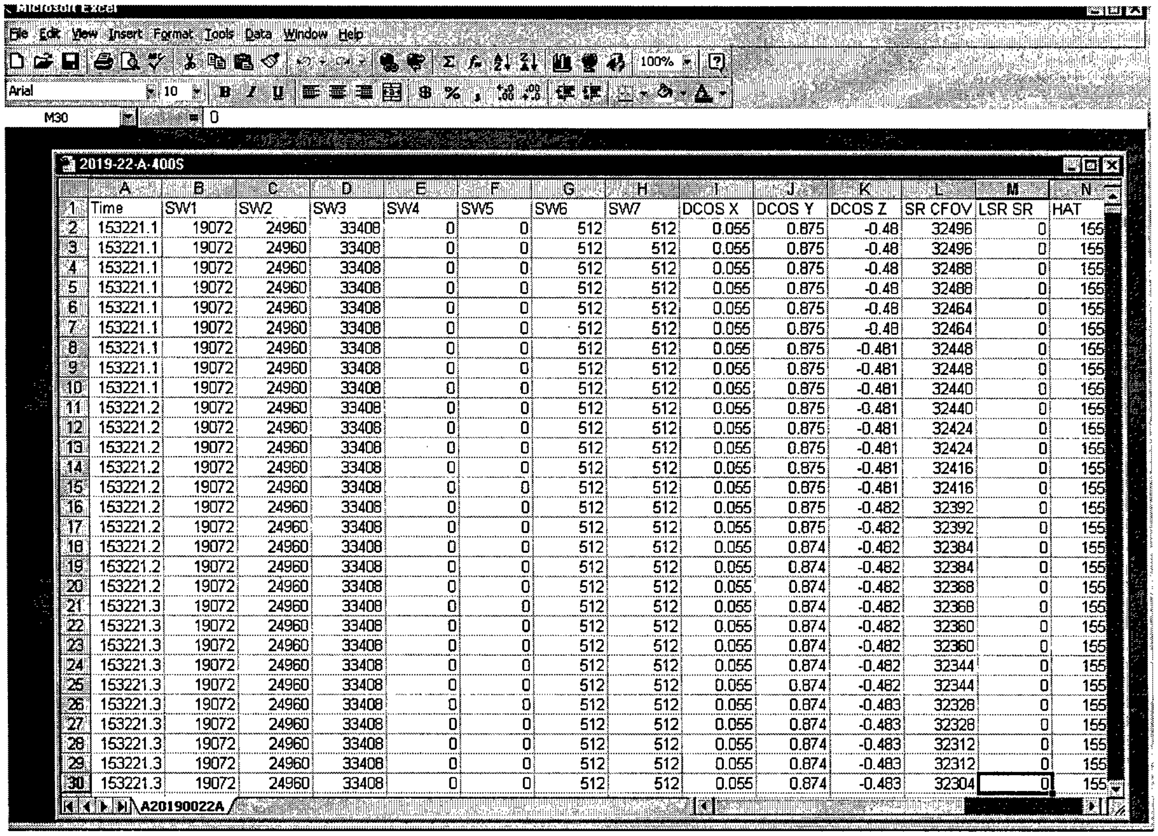


Figure 11 Sample AMUX Input Worksheet



	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	Time	SW1	SW2	SW3	SW4	SW5	SW6	SW7	DCOS X	DCOS Y	DCOS Z	SR CFOV	LSR SR	HAT
2	153221.1	19072	24960	33408	0	0	512	512	0.055	0.875	-0.48	32496	0	155
3	153221.1	19072	24960	33408	0	0	512	512	0.055	0.875	-0.48	32496	0	155
4	153221.1	19072	24960	33408	0	0	512	512	0.055	0.875	-0.48	32488	0	155
5	153221.1	19072	24960	33408	0	0	512	512	0.055	0.875	-0.48	32488	0	155
6	153221.1	19072	24960	33408	0	0	512	512	0.055	0.875	-0.48	32464	0	155
7	153221.1	19072	24960	33408	0	0	512	512	0.055	0.875	-0.48	32464	0	155
8	153221.1	19072	24960	33408	0	0	512	512	0.055	0.875	-0.481	32448	0	155
9	153221.1	19072	24960	33408	0	0	512	512	0.055	0.875	-0.481	32448	0	155
10	153221.1	19072	24960	33408	0	0	512	512	0.055	0.875	-0.481	32440	0	155
11	153221.2	19072	24960	33408	0	0	512	512	0.055	0.875	-0.481	32440	0	155
12	153221.2	19072	24960	33408	0	0	512	512	0.055	0.875	-0.481	32424	0	155
13	153221.2	19072	24960	33408	0	0	512	512	0.055	0.875	-0.481	32424	0	155
14	153221.2	19072	24960	33408	0	0	512	512	0.055	0.875	-0.481	32416	0	155
15	153221.2	19072	24960	33408	0	0	512	512	0.055	0.875	-0.481	32416	0	155
16	153221.2	19072	24960	33408	0	0	512	512	0.055	0.875	-0.482	32392	0	155
17	153221.2	19072	24960	33408	0	0	512	512	0.055	0.875	-0.482	32392	0	155
18	153221.2	19072	24960	33408	0	0	512	512	0.055	0.874	-0.482	32384	0	155
19	153221.2	19072	24960	33408	0	0	512	512	0.055	0.874	-0.482	32384	0	155
20	153221.2	19072	24960	33408	0	0	512	512	0.055	0.874	-0.482	32368	0	155
21	153221.3	19072	24960	33408	0	0	512	512	0.055	0.874	-0.482	32368	0	155
22	153221.3	19072	24960	33408	0	0	512	512	0.055	0.874	-0.482	32360	0	155
23	153221.3	19072	24960	33408	0	0	512	512	0.055	0.874	-0.482	32360	0	155
24	153221.3	19072	24960	33408	0	0	512	512	0.055	0.874	-0.482	32344	0	155
25	153221.3	19072	24960	33408	0	0	512	512	0.055	0.874	-0.482	32344	0	155
26	153221.3	19072	24960	33408	0	0	512	512	0.055	0.874	-0.483	32328	0	155
27	153221.3	19072	24960	33408	0	0	512	512	0.055	0.874	-0.483	32328	0	155
28	153221.3	19072	24960	33408	0	0	512	512	0.055	0.874	-0.483	32312	0	155
29	153221.3	19072	24960	33408	0	0	512	512	0.055	0.874	-0.483	32312	0	155
30	153221.3	19072	24960	33408	0	0	512	512	0.055	0.874	-0.483	32304	0	155

Figure 12 Sample AMUX data

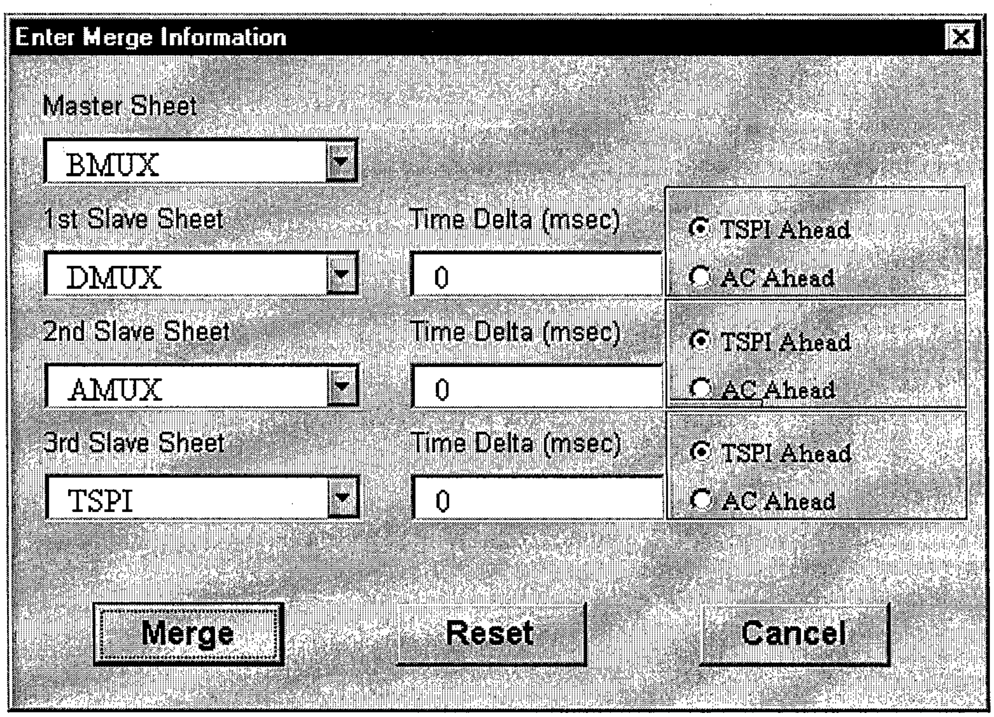
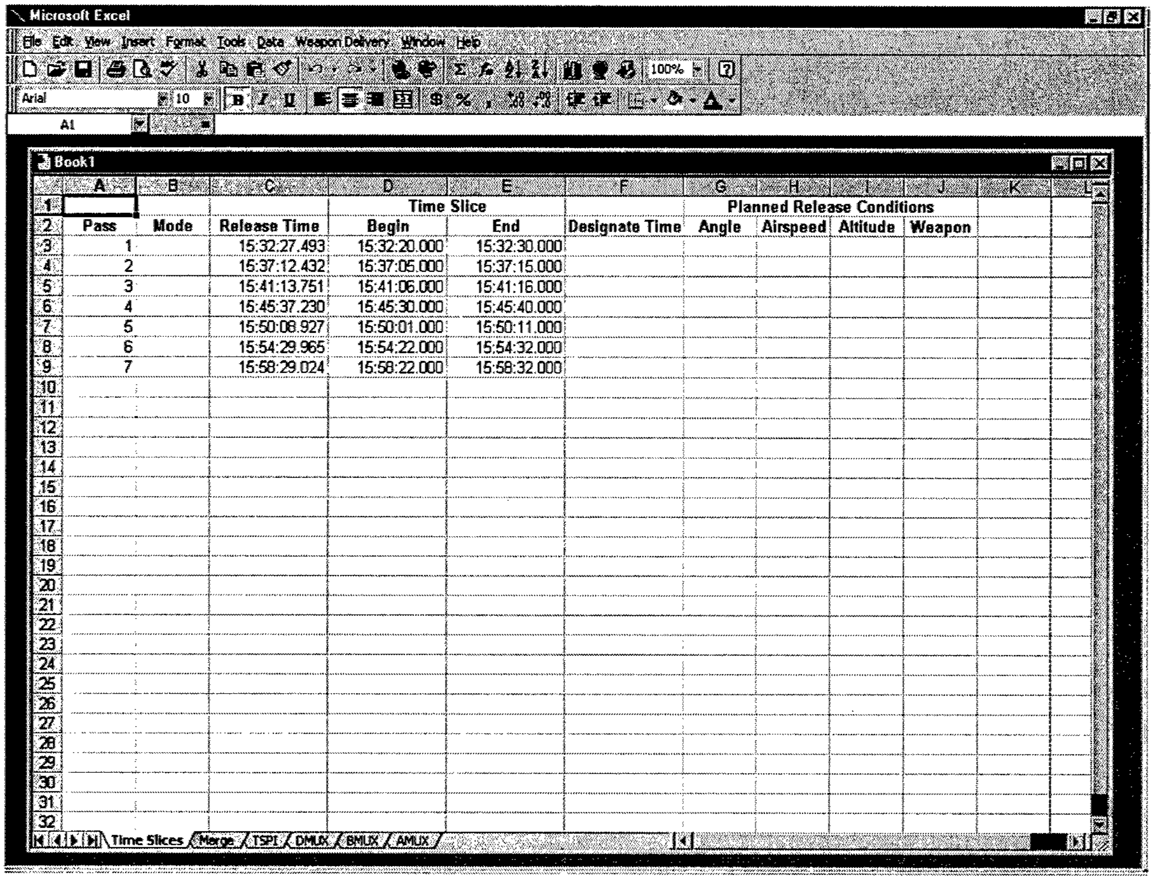


Figure 13 Merging window display

Once the data is merged, the selected time slices which had been identified during video review are input (Figure 14) so that the results are limited to the time segments for which the analysis is to be performed. By providing additional information, this spreadsheet or VBA code can also be used for analysis of weapon deliveries.



Pass	Mode	Release Time	Time Slice Begin	Time Slice End	Designate Time	Planned Release Conditions Angle	Airspeed	Altitude	Weapon
1		15:32:27.493	15:32:20.000	15:32:30.000					
2		15:37:12.432	15:37:05.000	15:37:15.000					
3		15:41:13.751	15:41:06.000	15:41:16.000					
4		15:45:37.230	15:45:30.000	15:45:40.000					
5		15:50:08.927	15:50:01.000	15:50:11.000					
6		15:54:29.965	15:54:22.000	15:54:32.000					
7		15:58:29.024	15:58:22.000	15:58:32.000					

Figure 14. Time Slice Inputs

7.2 Results

The results of the analysis are shown in the figure 15 below.

8.0 ACKNOWLEDGEMENT

The authors would like to acknowledge the prior contributions made by Steve Martin and Pat Cronin in the development of the original work tool and the analysis plan. Their previous work provided the basis of the current efforts.

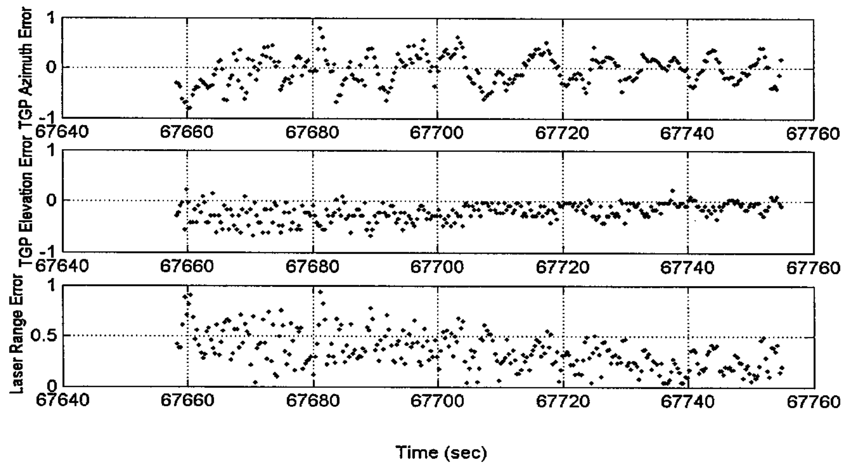


Figure 15. Typical TGP analysis results (normalized)